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Operational Aspects of Experimental Accelerator Physics

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Contents

1 <u>Introduction</u>

During the normal course of high energy storage ring operations, it is customary for blocks of time to be allotted to something called “machine studies,” or more simply, just “studies.” It is during these periods of time that observations and measurement of accelerator behavior are actually performed. Almost invariably these studies are performed in support of normal machine operations. The machine physicist is either attempting to improve machine performance, or more often trying to recover previously attained “good” operation, for example after an extended machine down period. For the latter activity, a good portion of machine studies time is usually devoted to “beam tuning” activities: those standard measurements and adjustments required to recover good operations.

Before continuing, please note that this paper is not intended to be comprehensive. It is intended solely to reflect one accelerator physicist’s impressions as to what goes on in an accelerator control room. Many topics are discussed, some in more detail than others, and it is not the intention that the techniques described herein be applied verbatim to any existing accelerator. It is hoped, however, that by reading through the various sections, scientists, including accelerator physicists, engineers, and accelerator beam users, will come to appreciate the types of operations that are required to make an accelerator work.

A second caveat is that the author is a shameless advocate of electron and positron machines, and synchrotron radiation sources in particular. Concepts such as transition energy, emittance dilution, and stochastic cooling, and devices such as Schottky pickups and flying wires are not discussed.

2 Orbit Measurement and Correction

2.1 Beam Position Monitoring Systems

The purpose of a beam position monitoring (BPM) system is to measure the transverse (x,y) coordinates of the beam centroid at a fixed number of locations along the storage ring's circumference. The set of numbers resulting from such a measurement is stored in a computer file, and is commonly referred to as an orbit.

2.1.1 BPM Sensors

To measure beam position, sensors or pickup electrodes (PUE's) of some type are required. There are two standard PUE types: capacitive button pickups, or stripline pickups. A button pickup consists of a metal disc (button) mounted on the end of a coaxial vacuum electrical feedthrough's center conductor. The button is usually located tangent to the inner surface of the storage ring vacuum chamber. A coaxial cable is attached to the vacuum feedthrough, and routes the button signal to the BPM processing electronics.

A stripline pickup (ref 1) consists of a metal strip running parallel to the beam motion inside the vacuum chamber and attached at one or both ends to the center conductor of a vacuum electrical feedthrough. The vacuum chamber forms a ground surface, so that the metal strip/vacuum chamber represents an electrical transmission line, usually with a characteristic impedance of 50 ohms. Stripline pickups have the property of being directional. They can be used to distinguish between positive and negative counter–rotating bunches in colliding–beam machines, with the signal from one beam appearing at one end of the stripline, and the counter–rotating beam's signal appearing at the other. The coaxial cables used to capture the signals must have the same characteristic impedance as the stripline, which is why 50 ohms is usually chosen.

Stripline electrodes are also commonly used as rf kickers. Pairs of electrodes driven in differential mode are used as transverse kickers and if driven using common mode, can be used as longitudinal kickers. A stripline pickup or kicker is commonly referred to as a "quarter–wave" stripline. This is because the narrow band coupling to the beam is maximum when the length of the stripline is equal to one quarter of a wavelength at the frequency of interest. For example, a quarter–wave stripline electrode to be used near 350 MHz ($\lambda \simeq 80$ cm) would work best with 20–cm–long electrode plates.

The intensity of signals induced on button or stripline pickups is roughly proportional to the transverse angle subtended, as seen by the beam.

Both button and stripline pickups are in principal broad–band devices. Button feedthroughs with good response to 12 GHz are commercially available, and stripline–type pickups with good response up to several GHz have been constructed. (ref 2,3) The signal induced on a button pickup is roughly proportional to the derivative of the bunch charge distribution ρ, i.e.,

$$V \sim \frac{d}{dt} \rho \, (s-\beta ct). \qquad [1]$$

Stripline pickups, on the other hand, produce a voltage proportional to the difference

$$\rho(s-\beta ct) - \rho\left(s-\beta c\left(t-\frac{2L}{c}\right)\right) \qquad [2]$$

where L is the stripline length. Note that the button signal is similar to that for a very short stripline.

2.1.2 BPM Signal Processing

At each BPM station around the circumference are located two or four pickup electrodes. A two–electrode arrangement can be used to measure either vertical or horizontal position by taking differences of button signals; top minus bottom or inside minus outside, respectively. A four–electrode arrangement can he used to measure both vertical and horizontal position simultaneously. Rather than position the four electrodes at top, bottom, inside, and outside, it is common to place the four electrodes in a rectangular arrangement; (Fig. 1) top inside, top outside, bottom inside, and bottom outside. With the button voltages from these four buttons defined as A,B,C, and D respectively, the vertical position will be proportional to A+B–C–D, while the horizontal position will be proportional to A–B+C–D. This configuration has the advantage that none of the buttons are heated by synchrotron radiation, in electron or positron machines, and the electrodes are generally closer to the beam for elliptical or rectangular vacuum chambers, improving sensitivity.

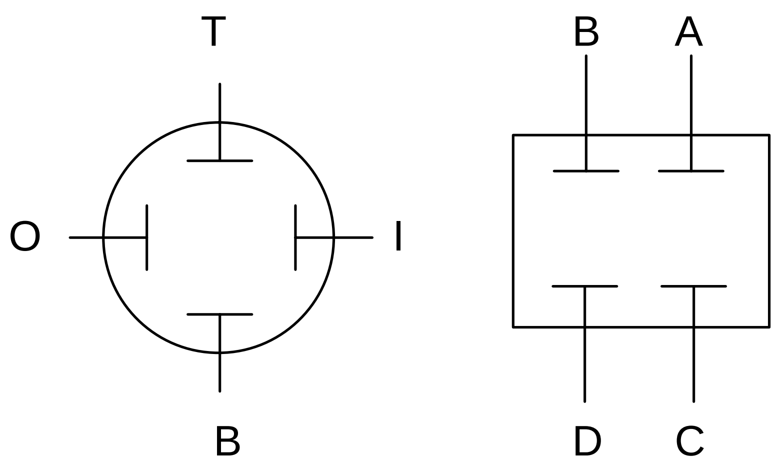

Figure 1 Pickup Electrode Arrangements

In most position monitoring systems, the difference signals are normalized either by dividing by the sum in software or by using a hardware normalization scheme, e.g., AM/PM conversion or log ratio processing. (ref 4, 5)

Due to the size of most high energy storage rings, there are always a large number of PUE signals to be processed. Because of this, many BPM systems employ some form of multiplexing. In the most extreme case, a network of coaxial rf switches is arranged so that every pickup signal can be sequentially connected to a common signal detector. The procedure of “taking an outbit” reduces to a problem of exercising all of the switches in the most efficient manner.

This kind of multiplexed BPM system has the great advantage of low cost. Total cable length is kept to a minimum and only a single, high quality detector is required plus some finite number of high quality rf switches.. The rf switches and their associated control electronics are in fact where the bulk of the money is spent. Another advantage of this type of system is that no detector matching is necessary, since all signals are measured by the same unit. It is important, however, that certain rf switching paths be made identical.

The primary disadvantage of a multiplexed system is its speed. It is not uncommon to spend several minutes of valuable machine study time waiting for an orbit measurement to be completed. If a lot of orbit work is required, a shift gets rapidly used up. In addition, it is impossible to observe real–time orbit motion, i.e., beam motions occurring more rapidly than a drift with several–minute time scale.

The other extreme of PUE networking is full blown parallel processing. The trend these days seems to be moving toward real–time (even turn–by–turn) orbit measurement. To do this, each BPM station (comprised of four PUE’s) must have its own dedicated processing electronics. Examples are the switched receivers with AGC used at Brookhaven’s National Synchrotron Light Source (ref 6) and ESRF at Grenoble, France. (ref 7) Log–ratio processing (ref 5) and AM/PM conversion (ref 4) are also examples of technologies that can be used in a parallel processing scheme.

In addition to heterodyne receivers, AM/PM converters, and log–ratio processing, a fourth option is stretcher or peak detector. Diode–based detectors have been reliably used both in multiplexed systems and for dedicated real–time processing at Cornell and Stanford. (ref 8) Diode detectors commonly use amplifiers and switchable attenuators to extend their dynamic range, contributing their own set of problems.

It is not uncommon for BPM networks to be a “compromise” system. At Cornell, for example, the ring is broken up into a number of sectors, with each sector having its own multiplexed processor.

Important features of any BPM system are its dynamic range (both position and intensity), resolution, and accuracy. It is common for most BPM systems to have a dynamic range in intensity near 40 dB, otherwise known as a factor of 100. For position measurement, a typical dynamic range is +/–20 mm, selected to be some reasonable fraction of the usable vacuum chamber aperture. The resolution of a BPM system is a measure of the smallest resolvable beam motion that can be detected. The accuracy relates to error between the measured beam position and the true beam position relative to an absolute position reference such as a survey monument or the magnetic centerline of a nearby quadrupole. The accuracy (e.g., in microns) is always greater than or equal to the resolution. Modern accelerator BPM systems have resolutions approaching 5 to 10 microns and accuracies better than 150 microns.

2.2 Orbit Correction

2.2.1 Reference Orbit Determination

One of the most common procedures performed in a high energy accelerator control room is orbit correction, or flattening. Shortly after commissioning an accelerator, a “reference orbit” is established. This reference orbit is simply a set of BPM readings deemed desirable for various reasons. Usually, the reference orbit is believed to be the orbit that agrees most closely with the magnetic centerlines of the storage ring quadrupoles and sextupoles, thus yielding the most linear optics. This is commonly the case in high energy colliders. For a synchrotron radiation source, on the other hand, the reference orbit is usually the orbit where all operational photon beamlines are adequately illuminated. Ideally, this orbit passes close to the quadrupole and sextupole magnetic centerlines, as in HEP machines. Determination of the reference orbit can be quite involved, and typically must be repeated many times over the life of an accelerator, simply because things move.

The magnetic centerline of a quadrupole can be found using the beam, by taking advantage of the fact that a quadrupole will not steer unless the beam is off center. The technique requires that a BPM be located adjacent to the quad in question, and that the quad be independently controllable (as compared to a string of quads wired in series). In addition, at least one other BPM elsewhere in the ring is required, if not a complete orbit. If a single BPM is used, it should be placed an appropriate fraction of betatron wavelengths from the quad in question and it, as well as its associated electronics, must be reliable. Finally, a means of moving the beam at the quad with high resolution is needed. This can be done using a local bump (see Section 2.2.3). A global orbit distortion can be used, but is less desirable.

Suppose the magnetic centerline of quad Ql is to be determined in the vertical plane. Define the vertical position of the beam as measured by the BPM adjacent to Ql to be Yl, and the vertical position at some other location in the ring to be Y2. Suppose further that a local close-dorbit distortion (local bump) exists, comprised of at least three steering elements with appropriate weights, simultaneously variable, implemented by using a computer–read software “knob,” for example. The bump is used to vary Yl and the quadrupole power supply varies Y2, unless of course the position Yl corresponds to the magnetic centerline of Ql. This is in fact the purpose of the measurement: to find the value of Yl where Y2 is independent of the strength of Ql. It is crucial that Y2 have a betatron phase such that the orbit distortion caused by Ql be large at the azimuth (s–value) of Y2, i.e., Y2 cannot be at a node.

This measurement can be made in a stepwise fashion, e.g., vary the bump, measure Yl, move Ql plus and minus and find the change in Y2, then repeat for a new Yl. A plot of ΔY2/ΔQ1 vs. Yl will intersect the Yl axis at a value of Yl corresponding to the magnetic centerline of Ql. This whole procedure must be repeated for all the quads in the ring, thus establishing the reference orbit described earlier. Obviously, the value of computer automated measurement cannot be emphasized enough. A technique similar to this is used at Cornell to determine magnetic centerlines with an accuracy of +/–100 microns. (ref 8)

At Brookhaven’s NSLS x–ray ring, a two–dimensional mapping procedure is used to determine the vertical reference orbit. Two vertical steering corrector magnets located an odd number of betatron quarter wavelengths apart are chosen, call them Cl and C2. A grid is set up, with Cl values plotted orthogonal to C2 values, and a total of about half a dozen values are selected for each corrector. For each of the 36 points on the grid, orbits are measured and photon observations are made at all operational photon beam lines. Each beamline reports back those grid values where a reasonable amount of illumination is observed. Since each beamline is observing photons from a single bending magnet, BPM readings upstream and downstream of that dipole corresponding to the best illumination are the values to be used for the reference orbit.

Compiling all the information from the beamlines produces a complete reference orbit for the vertical plane. (Many synchrotron radiation users are relatively insensitive to horizontal orbit.)

2.2.2 Global Orbit Correction

Once a reference orbit has been established and stored in a computer file, orbit corrections can be made. There are probably as many orbit correction algorithms as there are accelerators, but every scheme uses some sort of response matrix. The most brute force form of response matrix M_{ij} might be defined to be the number of millimeters of motion at BPM number i caused by a 1–ampere change in current through steering corrector coil j. If the numbers of BPMs and correctors are equal, then a desired beam motion represented by a vector X_i can be uniquely accomplished by using a set of steering corrector current changes represented by a vector $C_j = M_{ij}X_i$. The response matrix is determined empirically or semi–empirically, since calculated beta functions and phases very rarely agree with those actually observed (see Section 6.3).

The variety in orbit correction schemes derives from the fact that the numbers of monitors and correctors are by and large not equal and that other constraints need to be imposed. Steering corrector magnet power supplies are limited in the amount of current they can supply and this must be taken into consideration during orbit correction. In addition, steering correctors can be used to make small changes in the machine's dispersion function, making dispersion correction possible.

Orbit correction is an iterative procedure. Depending on the amplitude of the orbit change, it may take several "corrections" to achieve the desired result because of inherent nonlinearities of the accelerator lattice and BPM's and inaccuracies in the lattice model (i.e., the M_{ij}'s).

2.2.3 Local Orbit Correction

What has just been described could be called "global orbit correction." It is often desirable to make a local correction encompassing only a small fraction of the ring's circumference, for example to align a single synchrotron radiation beamline. To accomplish this, various combinations of three–element bumps are used. A bump is a closed–orbit distortion resulting from simultaneously changing three or more steering correctors. The simplest three–element bump consists of three equally spaced corrector magnets with no focusing or nonlinear elements between. If the three correctors steer through angles θ, -2θ, θ, a simple triangular orbit distortion is set up. In general, the ratios of steering corrector strengths needed for three–element bump closure, otherwise known as "bump coefficients," are given by the law of sines as follows:

$$\frac{\Delta x'_1 \sqrt{\beta_1}}{\sin\ \phi_{23}} = \frac{\Delta x'_2 \sqrt{\beta_2}}{\sin\ \phi_{31}} = \frac{\Delta x'_3 \sqrt{\beta_3}}{\sin\ \phi_{12}} \quad [3]$$

where the $\Delta x'_i$ are the deflection angles caused by the three correctors, the β_i are their corresponding beta function values, and ϕ_{ij} is the betatron phase advance between correctors i and j. (ref 9)

The coefficients resulting from these formulae give a good starting point for an empirical determination. At Brookhaven's National Synchrotron Light Source, the following procedure is used to establish bump closure. (ref 10) After selecting the three corrector magnets, two BPMfs located outside the bump are chosen, with some odd multiple of 90 degrees of betatron phase between them. A 3x2 transfer matrix is then measured, giving the amount of position change caused at the two BPM's by each of the three correctors. From this, first–order bump coefficients are extracted by requiring zero motion at the two BPM's when moving the three corrector magnets simultaneously. Larger and larger amplitude bumps are implemented, each time making small corrections to the bump coefficients in order to minimize motion at the two BPM's. The result is a three–element bump that does not affect the beam at the two external BPM's**,** which is equivalent to bump closure.

Superposition of two three–element bumps having two correctors in common yields a four–element bump. Considering two simple triangle bumps as described above, it is easy to see how four–element "angle" and "parallel translation" bumps can be formed simply by the subtraction or addition of corrector weights from two three–element bumps. The "angle" and "parallel translation" refer to the midpoint of the four correctors. These types of four–element bumps are quite useful for aligning synchrotron radiation insertion device beamlines, where the radiation source typically is located in the center of a long symmetric straight section of the ring.

3 Betatron Tune Measurement

3.1 Preliminary

A time–dependent deflection can be used to measure the vertical and horizontal tunes. Recall that the tune is defined to be the number of betatron oscillations executed by an off–axis particle in traveling one turn around the storage ring.

Consider a time–dependent steering element, such as a stripline kicker, varying as $\cos(\omega t)$. The equation of motion for transverse position of a bunch can be written as:

$$\frac{d^2\chi}{d\phi^2} + \nu^2\chi = \sqrt{\beta_c}\ \Delta x' \sum_{n=-\infty}^{\infty} \delta(\phi-2\pi n)\cos n\omega T_0 \qquad [4]$$

where is the Courant–Snyder variable $x/\sqrt{\beta}$, ϕ is the betatron phase divided by ν,ν is the tune, and T_o is the revolution period. The quantity β_c is the value of the beta function at the kicker, and $\Delta x'$ is the maximum deflection angle achieved during one cycle, in radians. The kicker is assumed to have zero length, so that its effect on the beam is that of an impulse. Damping is ignored for the present.

The above equation is not too hard to solve using Fourier transforms and a few δ function identities. The result is

$$\chi(\phi) = \frac{\sqrt{\beta_c}\ \Delta x'}{2\pi} \sum_{m=-\infty}^{\infty} \frac{\cos\left(\frac{\omega}{\omega_o} + m\right)\phi}{\left(\frac{\omega}{\omega_o} + m\right)^2 - \nu^2}, \qquad [5]$$

using $\omega_o = 2\pi/T_{o.}$

This equation exhibits the phenomenon of resonance, which is not surprising since all we do is excite a harmonic oscillator (the beam) with a sinusoidal drive (the stripline). Because we use an impulse at a fixed azimuth in the ring, a multitude of resonances are excited. The locations of these resonances can be found by setting the denominator to zero:

$$\omega = m\omega_o \pm \nu\omega_o. \qquad [6]$$

This equations clearly shows what are commonly called “betatron sidebands” living above and below each harmonic of the fundamental.

The equation for $\chi(\phi)$ is not the end of the story, however, since it does not include a description of the beam’s bunch structure. If one were actually to look at the signal from a single BPM button pickup, for example, one would see a voltage resembling the following, assuming zero bunch length:

$$V(t) \simeq \text{const.} \frac{d}{dt} \sum_{m=-\infty}^{\infty} \sum_{n=0}^{B-1} I_n \, \delta\left(t - mT_o - nT_o/B\right) \tag{7}$$

where m labels the turn number, n is the bunch index, I_n is the bunch current, and B is the total number of bunches. Fourier transforming the above expression gives some idea of what you would see if you hooked up the output of the button to the input of a spectrum analyzer:

$$V(\omega) \sim \text{const.} \cdot \omega \cdot \sum_{m=-\infty}^{\infty} \delta\left(\omega - \frac{2m\pi}{T_o}\right) \sum_{n=o}^{B-1} I_n e^{in\omega T_o/B}. \tag{8}$$

The expression clearly shows the harmonics of the revolution frequency, as well as the effect of bunch–filling patterns. As an example, observe what happens when a two–bunch pattern (B=2) is used with equal current in each bunch. The sum over n becomes

$$\sum_n I_n \, e^{in\omega T_o/B} = 1 + e^{i\omega T_o/2}. \tag{9}$$

Note how this expression vanishes for ω T = (2k+1)π. In other words, all odd rotation harmonics drop out for two equally spaced bunches. Similarly, if one were to fill every rf bucket equally, i.e., B = h, where h is the harmonic number, one would discover that all harmonics drop out except multiples of the rf frequency (proof of this is left as an exercise).;

A real–time difference of two button signals (say top and bottom) would have all of the spectral characteristics of the bunch structure, in addition to the betatron sidebands caused by the time–dependent kicker. One typically sees enormous spectral lines at revolution harmonics, and the kicker strength must be turned up enough to bring the betatron sidebands up above the noise threshold of the system. A measurement of the frequency of these sidebands yields the fractional part of the tune according to

$$\nu = \Delta\omega/\omega_o \tag{10}$$

where $\Delta\omega$ is the distance from a sideband to the nearest (ν<1/2) or second–nearest (ν>1/2) harmonic of the revolution frequency ω_o. The ambiguity ν<1/2 or ν>1/2 can be resolved by changing quadrupole strengths and paying close attention to the sign of the resulting change in tune. For example, increasing a horizontally focusing quad (QF) or string of quads is known to increase the horizontal tune. In this situation, the horizontal betatron sidebands will move outward from their associated revolution harmonic, i.e., ν_H must <u>increase</u>. A similar procedure can be used vertically. The only fly in the ointment is when the machine is fully coupled and both horizontal and vertical sidebands ν_H and ν_v appear in equal strengths, regardless of which plane is being driven. For this, one can use the fact that the horizontal tune moves up more than the vertical tune moves down when the horizontal focusing is increased. More commonly, a software knob is used to vary focusing and defocusing quads QF and QD simultaneously so that the horizontal and vertical tunes can be varied independently in an orthogonal manner.

If the integer part of the tune is desired, it can be found by observing the orbit distortion caused by changing a single steering corrector and counting the number of oscillations.

3.2 Betatron Tune Measurement Instrumentation

To measure the tune, a transverse drive system, a real–time beam position sensor, and a device for measuring transfer function are required. The drive system consists of a drive element and an amplifier. If striplines are used, the system will operate at rf frequencies up to approximately 500 MHz. The stripline drive is usually designed to work best at frequencies near the machine's rf frequency, i.e., its length is one–fourth of an rf wavelength. It is not necessary to use such high frequencies, however, since all revolution harmonics have associated sidebands. A system operating near low harmonics of the revolution frequency (up to a few MHz) can be designed relatively inexpensively. Instead of a stripline kicker, a fast "shaker" magnet using ferrites in conjunction with a ceramic vacuum chamber section can be used.

The real–time beam position sensor can take the form of one of the standard BPM system detectors, assuming it has enough bandwidth, or a dedicated stripline pickup/rf hybrid combination can be used. The hybrid is used to take a real–time difference of two stripline signals (e.g., top – bottom). These hybrids can be quite broadband, using ferrites in a difference transformer up to a few hundred MHz, or octave bandwidth devices using stripline technology are common (e. g. , rat–race hybrids) . For the purposes of tune measurement, normalization of the difference signal is unnecessary.

The beam position sensor used at KEK's Photon Factory in Tsukuba, Japan for tune measurement is an x–ray beam position monitor sensing synchrotron radiation photons. (ref 11) The popularity of synchrotron light sources has resulted in a variety of different designs for photon BPM's. Because of the long source–to–monitor lever arm, photon BPM's are highly sensitive to angular electron or positron beam motions; therefore a much smaller drive amplitude is required for a tune measurement than for rf BPM's.

The device for measuring transfer function can be an in–house design, but many such devices are available commercially. Quite common is a spectrum analyzer/tracking generator combination. The tracking generator output drives the power amplifier/stripline kicker input, while the beam position signal is sensed by the spectrum analyzer. This type of device can be found for either low frequency or rf. Also popular are rf network analyzers which can be used with an S–parameter test set to measure S21 (forward transmission coefficient) of the network comprised of drive system, beam, and position sensor. All such transfer function devices measure the ratio of beam position to drive voltage in one form or another.

A "tune measurement system" is actually two systems, one for each transverse plane. Ideally, these systems are dedicated and are conveniently interfaced to the accelerator control system computer.

4 Synchrotron Tune Measurement

The previous discussion assumed that the period of revolution of the beam centroid is a constant. In many machines, the beam spontaneously undergoes small phase oscillations known as synchrotron oscillations, so that the signal observed on a button pickup takes the following form for single–bunch operation:

$$V(t) \sim \text{const.} \frac{d}{dt} \sum_{m=-\infty}^{\infty} \delta(t - mT_o - \tau \cos\omega_s t) \qquad [11]$$

where ω_s is the angular frequency of synchrotron oscillations and τ the amplitude in seconds. The synchrotron tune is defined to be the ratio of the synchrotron frequency to the revolution frequency, and it is usually quite small. Typically the synchrotron frequency is a few kilohertz, so that if the revolution frequency is several hundred kilohertz, ν_s is on the order of 0.01 or less.

If the Fourier transform of the above expression is performed (which will not be attempted here), one discovers that all of the revolution harmonic spectral lines are still present, but that in addition each line is surrounded by synchrotron sidebands. They occur at frequencies

$$\omega = n\omega_o + m\omega_s. \qquad [12]$$

In addition, the amplitudes of the sidebands decrease as m increases, with an envelope described by a Bessel function.

The instrumentation used for measuring synchrotron frequency is similar to that for betatron tune measurement, except that quite often the synchrotron oscillations are self–excited and can be measured using a spectrum analyzer with no drive. In fact, it is quite common for elaborate feedback systems to be constructed for the express purpose of damping the spontaneous synchrotron oscillations. (ref 12) The spontaneous oscillations are driven from a number of sources including phase noise on the accelerator's rf system and bunch–to–bunch wakefields.

If one were interested in driving a synchrotron oscillation, it could be done by modulating the phase control voltage of the rf system's, phase lock feedback loop, or by driving a pair of stripline kickers in a common–mode configuration. In some accelerators, special purpose rf cavities are designed to couple to the beam more efficiently for feedback.

A major problem confronted when attempting to measure very small synchrotron oscillations is the fact that the synchrotron sidebands are so close to their associated revolution harmonics, i.e., the synchrotron frequency is much less than the revolution frequency. Because the revolution harmonic lines are so huge in comparison to the synchrotron lines, a very deep and narrow bandwidth filter is required to separate them. This is especially important from the context of feedback system design. A filter for the NSLS VUV ring was constructed using a low loss transmission line together with an rf hybrid. (ref 13) The signal from a stripline pickup electrode was delayed by exactly one revolution period with the coaxial transmission line, and then subtracted from itself one turn later using the hybrid.

Using this, a 60–dB–deep notch filter was constructed, effectively eliminating the first revolution harmonic line from the signal. What results is a signal representing the change from one turn to the next, which can be put to use in a synchrotron oscillation feedback system.

5 Beam Intensity Measurement

One of the most important parameters of an accelerator is beam lifetime. Due to finite aperture in combination with scattering from gas molecules, nonlinear fields, and other effects, the beam has a finite, but hopefully long lifetime. To measure a long lifetime, a very high resolution beam intensity monitor is required. (ref 14) High quality current transformers (DCCT's), are now commercially available, and are capable of measuring a change in current as small as 5 microamperes over a dynamic range of several hundred milliamps. (ref 15) These devices are usually configured as a toroid of magnetic material through which the beam passes. The beam vacuum chamber must be broken electrically by using a ceramic insert, and the signal is detected by using the toroid windings, along with some exotic electronics.

For a pulse measurement, a toroid produces a pulse that can be integrated for bunch charge measurement or peak detected for bunch peak current measurement, which depends on bunch length. This becomes important for multibunch operation, when it is desired to “top off” the different bunches to carry equal charge. Pulse measurements by nature have less resolution than DCCT’S.

A stripline monitor can also be used for beam intensity measurement. Running the sum of a pair of electrodes (say top and bottom) using an rf hybrid into a spectrum analyzer, it is easy to show that the heights of spectral lines corresponding to multiples of the rf frequency are always proportional to total beam current. This measure of intensity is independent of beam position between the stripline plates, to first order. A similar measurement could be done using button pickups; however, stripline response lends itself well to narrow band measurements, especially if the stripline length is chosen to be a quarter of an rf wavelength.

5.1 Intensity Monitor Application

A common use of pulse charge monitors is to measure injection/extraction efficiency. High energy storage rings require elaborate injectors, sometimes involving two or three lower energy accelerators. During the process of injection tuning, it is helpful to know how much charge actually gets from one accelerator to the next, and what fraction of charge going into an accelerator eventually gets extracted for the next stage. Here it is important to have intensity monitors whose calibrations are closely matched.

A somewhat less common measurement involving intensity monitor is scraper–lifetime measurement. A scraper is simply a movable aperture that can be inserted into the accelerator vacuum chamber with a very accurately known transverse position. The concept is quite simple: to obtain a plot of beam lifetime vs. scraper position.

A number of subtleties complicate matters, however. First of all, beam lifetime depends on vacuum and, for positron and electron accelerators, vacuum depends on beam intensity because of vacuum chamber outguessing from synchrotron radiation. Therefore, to get a snapshot of lifetime vs. scraper position at fixed beam current, the measurement must be performed in a very short time. This becomes critical when short lifetimes are being measured. The data must be collected before the vacuum system has a chance to recover from the higher current gas load. Second, one would like to measure scraper position relative to the beam centroid. Because the beam is usually off–axis, care must be taken to very accurately determine the beam–scraper relationship. If two opposing scrapers are available at the same location in the ring, the beam centroid can be found from the two sets of scraper lifetime data.

Scraper lifetime data for electron and positron machines have three qualitatively different regions. When the scraper is far from the beam, it has no effect on the lifetime. This is because it is outside the accelerator’s acceptance: the beam halo is being clipped elsewhere in the ring, probably at a high β point or some other limiting aperture. The point at which the scraper enters the beam’s halo and starts to affect lifetime is a direct measure of the acceptance. The distance to the beam centroid squared and divided by the value of beta at the scraper yields the acceptance of the machine in meter–radians. Beyond this point, the lifetime is proportional to the acceptance, which is now determined by the scraper. This effect can be calculated from the theory of elastic Coulomb scattering off of residual gas molecules, which is the mechanism responsible for the beam halo. (ref 16) Eventually, the lifetime drops like a rock. This is the quantum lifetime regime, where the scraper begins to cut into the core of the beam itself. (ref 17)

6 Special Topics

6.1 Coupling

An important feature of all high energy storage rings is the phenomenon of transverse coupling. A skew quadrupole magnet is the simplest example of this: a horizontal displacement through such a magnet produces a vertical deflection and vice versa for a vertical displacement. This effect is easily observable if one introduces a deflection using a horizontal steering magnet, for instance, and then measures the resulting orbit distortion. For an ideal machine, the horizontal orbit will be affected but not the vertical. All machines will, however, exhibit a small vertical orbit distortion due to small imperfections in the lattice, nonlinearities, or skew quadrupole magnets.

As a simple model, consider two coupled harmonic oscillators labeled x and y:

$$\frac{d^2x}{d\theta^2} + \nu_x^2 x = \varkappa y, \qquad \frac{d^2y}{d\theta^2} + \nu_y^2 y = \varkappa x. \qquad [13]$$

The quantities x and y could represent the transverse displacement of a beam stored in a constant gradient machine where the focusing is evenly distributed around the circumference, κ denotes a small coupling term, and ν_x and ν_y are the betatron tunes. The independent variable θ represents the azimuth of the beam around the (circular) accelerator in radians. Substituting sinusoidally varying functions for x and y, one arrives at a formula for the normal–mode "frequencies" ω:

$$2\omega^2 = \nu_x^2 + \nu_y^2 \pm \left[\left(\nu_x^2 - \nu_y^2\right)^2 + 4\varkappa^2\right]^{1/2}. \qquad [14]$$

Note first that if κ is much less than $|\nu_x - \nu_y|$, the two positive roots of this equation are very near ν_x and ν_y. Second, note that the distance of closest approach of the two normal–mode "frequencies" is a direct measure of the strength of the coupling. Specifically, if $\nu_x = \nu_y = \nu$, then

$$\omega^2 = \nu^2 \pm \varkappa, \qquad [15]$$

indicating that the distance of closest approach is 2κ.

Finally note that if the tunes ν_x and ν_y are varied together with opposite sense, and if they "cross," then the two normal modes actually exchange identities. This means that if one normal mode is initially associated, say, with ν_x, and ν_x is then changed to be equal to the old ν_y and vice versa, then the same normal mode will now have a frequency near the new ν_y. This is perhaps easiest to see graphically, by plotting ω vs. $\nu_x - \nu_y$ in Eq. [14].

Although derived from a very simplistic model, the previous observations are, in a narrow sense, true of real storage rings. The general theory indicates that a large number of "coupling resonances" are excited, and the complete solution involves summing a large number of them. (ref 18) One class of resonances, the difference resonances, occurs when vertical and horizontal tunes differ by an integer and have the same properties as those described in the preceding simple model.

Many storage rings are operated near a difference resonance because difference resonances are usually non–destructive (generally only increasing the vertical beam size) and because many resonances in the (ν_x,ν_y) plane are destructive but are sparsely located near the difference resonances. Because of this, and as a result of earlier observations, difference resonances can be used to "decouple" a storage ring.

It was mentioned in an earlier section that linear combinations of quadrupole magnets can be varied in such a way as to change the tune in one plane without affecting the other. In a completely analogous fashion, one can generate a software "knob" which varies the difference $\nu_x - \nu_y$ without affecting the sum, and vice versa. Declaring the $\nu_x - \nu_y$ knob to be the "delta" knob, and having access to horizontal and vertical tune measurements one can decouple a machine using skew quadrupoles. As few as two skew quads can be used, but it is more common to have two families of skew quads distributed around the ring with appropriate betatron phases separating them. (ref 19)

First, the tunes are brought together by using the delta knob. The distance of closest approach is a measure of the coupling as described before. Next, skew quads are varied with the objective of achieving the minimum possible "tune split." Note that the tune measurement system is actually measuring the normal–mode tunes, and not ν_x and ν_y. The procedure is iterated until an acceptable tune split is achieved. Finally, the tunes are pulled apart, back to their nominal values for normal operations. Associated with this last procedure is a dramatic collapse of the vertical beam size as viewed, for example, by a synchrotron light monitor.

Upon completion of the above procedures, the accelerator is deemed to be "globally decoupled," meaning that the accelerator as a whole is decoupled into orthogonal normal modes. A more detailed look shows that individual sections may require "local decoupling." For an overview of this procedure, the paper by Bagley and Reuben is quite good. (ref 20)

In addition to using tune measurement as a coupling diagnostic, one can also tune directly on vertical beam size, depending on the quality of available beam size monitors (synchrotron light, etc.). This is especially useful for on–the–fly tuning of colliding beam operations.

6.2 <u>Dispersion and Chromaticity</u>

An important aspect of any high energy storage ring is the dependence of its key parameters on beam momentum. Dispersion is a measure of the dependence of orbit on momentum, and chromaticity relates how the betatron tunes vary with momentum. To get a handle on either of these, one must first have a convenient method of varying the beam momentum by a small amount. For a fixed magnet lattice, small changes in revolution period T are related to small changes in momentum through the momentum compaction α:

$$\frac{\Delta T}{T} = \alpha \frac{\Delta p}{p} \qquad [16]$$

where p is the beam momentum. Proton storage ring people should forgive the author for assuming relativistic beam momentum, ignoring the velocity–dependent term to be added to α.) The momentum compaction is a lattice parameter relating how much orbit length increase is associated with a small increase in beam momentum. Finally, noting that a fractional change in rf frequency f_{rf} changes the fractional revolution period an opposite amount, one arrives at the following:

$$\frac{\Delta f_{rf}}{f_{rf}} = -\alpha \frac{\Delta p}{p}. \qquad [17]$$

Using a calculated value for α, one can change the beam momentum a known amount by changing the rf frequency.

The dispersion function $\eta(s)$ is defined according to

$$X_p(s) = \eta(s) \frac{\Delta p}{p} \qquad [18]$$

where $X_p(s)$ is the change in orbit around the machine when the momentum is changed an amount Δp. To measure dispersion, one usually changes the rf frequency positive and negative, taking the difference between orbits measured at the two extremes. Knowing the amount of rf frequency change and the momentum compaction, one can infer the dispersion.

Because most rings lie in a plane, dispersion is a horizontal effect. Changes in vertical orbit with momentum are usually associated with residual coupling or other lattice imperfections. The primary reason for being interested in dispersion, from an operational standpoint, comes into play when dispersion is discovered to be non–zero where it is not supposed to be. For example, non–zero dispersion at the location of an rf cavity can lead to undesirable coupling between transverse and longitudinal beam motion, the so–called synchrobetatron coupling. In addition, synchrotron light sources employing undulators and wigglers have as a constraint that the dispersion function vanish within the insertion devices. Otherwise, an unwanted increase in beam emittance results.

The chromaticity is defined to be the change in tune with momentum:

$$\Delta\nu = \xi \frac{\Delta p}{p} \qquad [19]$$

For machines containing no nonlinear elements, the chromaticity is a negative number (natural chromaticity) . This is because quadrupoles focus higher energy particles less than on–momentum particles. Introduction of sextupole magnets at dispersive points in the lattice allows one to vary the chromaticity. It is important to have slightly positive chromaticity in both x and y planes to control the fast head–tail instability. (ref 16)

To measure ξ, one usually plots about five values of tune vs. rf frequency and extracts the slope at the nominal operating frequency by fitting a polynomial. This is necessary because the tune is usually a highly nonlinear function of momentum.

6.3 Beta Function Measurement

6.3.1 Quadrupole Massage Technique

The standard beta function measurement technique for accelerators having independently controllable quadrupole magnet power supplies is to measure the change in betatron tune caused by varying the field strength of a single quadrupole. The result of this measurement is proportional to the beta function at the location of the quadrupole magnet which is being changed, (ref 17) according to

$$\Delta\nu = -\frac{1}{4\pi} \beta\Delta k \qquad [20]$$

where Δk is the change in the integrated quadrupole field gradient.

A potential difficulty with this technique is that hysteresis effects result in a nonlinear relation between the quadrupole current and the resulting magnetic field. In addition, the beta function is being measured at the location of the quadrupole magnet and not at the beam position monitors. Ultimately, the beta functions at the position monitors and correction dipoles are most relevant for orbit feedback systems. Finally, the measurement is complicated, involving about 100 power supplies, each of which must be varied in sequence. The process is time consuming and long time scale drifts in machine parameters, resulting from temperature variations, for example, can pollute the measurement.

6.3.2 Closed–Orbit Difference Technique

This technique takes advantage of a well–known formula for the closed–orbit distortion resulting from a change in a single steering element: (ref 17)

$$x = \Delta x'_c \frac{\sqrt{\beta_c \beta}}{2\sin(\mu/2)} \cos\left(|\phi - \phi_c| - \mu/2\right) \tag{21}$$

where β is the beta function at the beam position monitor where the beam motion x is observed, $\Delta x'_c$ is the angular deflection caused by the steering element, and β_c is the beta function at the steering element. The quantities ϕ and ϕ_c are the betatron phase at the beam position monitor and the steering element, respectively, and $\mu=2\pi\nu$ is the betatron phase advance per turn in radians (ν = "the tune").

Simply stated, the idea is to measure two perturbed orbits resulting from two different steering elements located some odd multiple of $\pi/2$ in betatron phase away from each other. If one knows the values of β_c and ϕ_c at these correctors, then one can extract both the beta function and the betatron phase at all functioning beam position monitors. Also, the tune must be measured. This technique was proposed by Harrison and Peggs. (ref 21) Additionally, the beta function on the x–ray ring at NSLS was measured with reasonable success by Decker and Swenson using a similar technique.

The advantages of the orbit difference technique are that the measurement is quick and is limited only by the quality of the orbit measurement system and two steering corrector power supplies.

One difficulty with this technique is that the β_c's and ϕ_c's are unknown. This can be resolved using a third closed–orbit measurement together with least squares fitting, but an ambiguity of scale still remains. Specifically, if β_c is scaled up by a factor g, and all β's are scaled down by g, then formula [21] indicates that a consistent solution can still be found. Also, nonlinearities are again a problem, but this time resulting from deliberately placed magnetic elements – sextupoles and octupoles. If the orbit perturbations are made too large, then the beta functions themselves will change as a result of nonlinear focusing. On the other extreme, if orbit perturbations are made too small, then one will obtain a very noisy measurement when trying to resolve tiny orbit motions. In addition to magnetic nonlinearities, one must contend with the inherent nonlinearities of the position monitor pickup electrodes and processing electronics for large orbit excursions.

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